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Sediment dynamics on the Northwest African continental margin

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ABSTRACT

The sedimentation regime off Northwest Africa is shaped by: (1) structural factors, which result in generally low relief on land, shelf widths between 40 and more than 120 km, and average slope inclinations between 1° 30′ and 3°; (2) land climates, which control the delivery of terrigenous particles to the margin; (3) water movements including boundary currents and upwelling; and (4) the post-Pleistocene sea level rise.

This chapter combines published and new results arising from research into the sedimentation processes off Northwest Africa, and emphasizes particularly the activities of the Kiel marine geological group during the past few years. Reviews of cruise activities and results were given in Closs *et al.* (1969) (*Meteor* cruise 8, 1967, off Morocco), Seibold (1972) (*Meteor* cruise 25, 1971, off Sahara to Central Senegal), Seibold and Hinz (1976) (*Meteor* cruise 39, 1975, and *Valdivia* cruise 10, 1975, from Morocco to South Senegal), and Walden *et al.* (1974) (*Meteor* cruise 30, 1973, off Sierra Leone).

Some of these cruises were used for pre- or post-site surveys for the Deep-Sea Drilling Project, or to add undisturbed Quaternary cores to the *Glomar Challenger* cores (leg 41, 1975; Lancelot, *et al.*, 1978); leg 47A, Arthur *et al.*, 1979; Lutze *et al.*, 1979).

We have concentrated our geological investigations on a number of standard profiles from the shelf to the upper continental rise as given in Figure 1. The manuscript was finished May 1979.

Morphology

Published bathymetric maps containing commentaries on submarine morphology are rare (Lisitzin, 1969; Rona, 1971; Egloff, 1972; Uchupi *et al.*, 1976). An excellent map (1:1 million) exists depicting the sea floor between 11° and 18°N off Senegal/Gambia (Marshall *et al.*, 1977). No equivalent map is published from off the Sahara farther north. Generally *shelfs* are narrow, with some exceptions near stable massifs as of the Reguibat High north and south of C. Blanc, and the Guinea Arch in the South. Shelf widths there exceed 120 km. Shelf break depths are about 110–120 m.

The *continental slope* drops to a maximum 4000 m water depth and can often be delineated only approximately. Slope angles may reach 5–6° as off Morocco (Figure 2, profile A) or off Casamance (Figure 2, G) as a result of young tectonism or of the existence of buried Mesozoic carbonate platforms with steep slopes. Most slope angles, however, are between 1 and 3°. Sometimes terrace-like features are observed. Seismic profiles off the Sahara (Figure 2 B–D, Seibold and Hinz, 1974) indicate that these step-like features may have originated from erosional events at slope bases during the Tertiary and by subsequent progradation. This mechanism was confirmed off C. Bojador (Figure 2, B) by DSDP Sites 369 and 397 (Arthur *et al.*, 1979).

South of C. Bojador to about 25°N the continental slope is dissected by many canyons, slope valleys, and gullies (Rust and Wieneke, 1973; Arthur *et al.*, 1979) indicating erosional destruction over wide areas. The incisions are concentrated in water depths of more than 1000 m (Figure 3). Only one valley reaches the shelf break. South of this area no

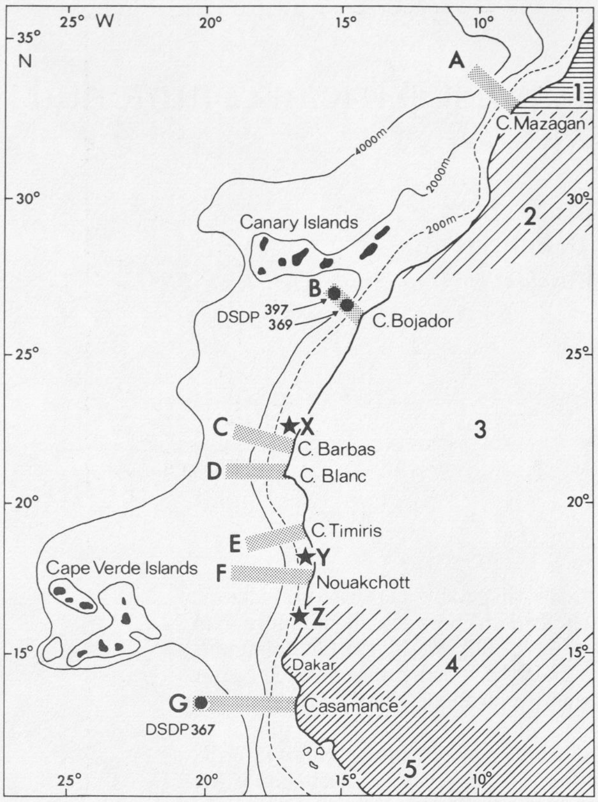

Figure 1 (1) Standard profiles, northwest African continental margin, Geological Institute, Kiel University. A, *Meteor* cruise 8, 1967; B, C, *Meteor* cruise 25, 1971; D, *Meteor* cruise 39, 1975; E, F, G, *Valdivia* cruise 3 1975; X, Y, Z, detailed shelf studies as mentioned on page 152

(2) Zonation of vegetation and climate: 1, Mediterranean scrub, warm-temperate, winter rain; 2, steppe, hot, summer dry; 3, desert, hot, dry; 4, steppe, hot, winter dry; 5, savannah, tropical, winter dry; Senegal mouth near Z (15° 47′N)

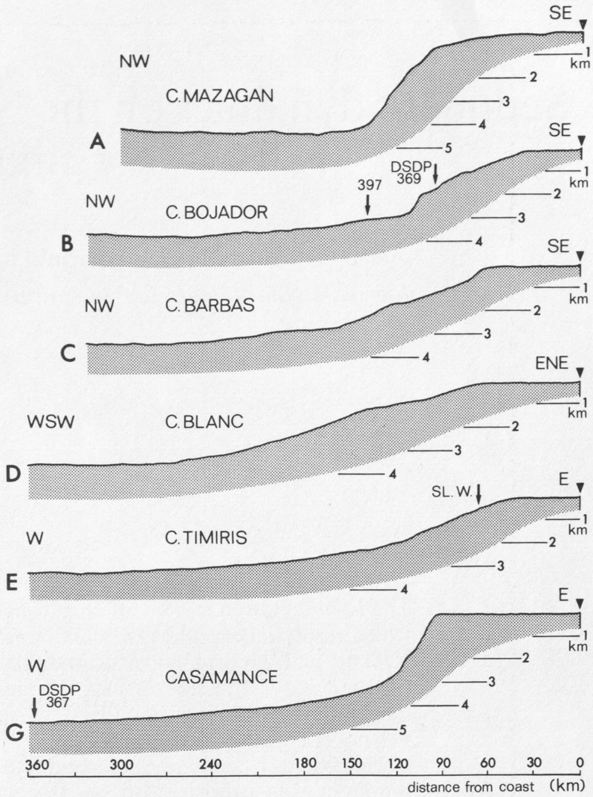

Figure 2 Continental margin profiles between Morocco and south Senegal. For location of profiles A–G see Figure 1; vertical exaggeration 15:1; SL.W., slope wall as mentioned on page 148

real canyons were found up to C. Blanc. From there to Southern Senegal canyons and other slope incisions are again widespread but they begin on the upper slope. The canyons off Tioulit (18°50′N), Nouakchott (18°05′N), four smaller off the Senegal mouth, off Cayar (15°N), and several smaller south of Dakar transect the edge of the shelf. Certainly the southern occurrences are a function of a higher former sediment supply.

An unexplained morphological feature is the 'slope wall' (Figure 2, E), first detected on profiles of the *Valdivia* 10-2, 1975 cruise. In about 500 m water depth the roughly 70 m high wall follows contours between 19° 40′N and 18° 30′N more or less continuously, mostly with landward and seaward depressions. Eventually the same feature was detected off C. Vert in 300–700 m water depth (Marshall *et al.*, 1977). The wall acts as a trap for grain-by-grain downslope movements (Bein and Fütterer, 1977).

Some morphological features of the upper continental rise are discussed on page 156.

Sediments

Grain size distributions or surface sediments are given in more detail in Summerhayes *et al.* (1976), Lange (1975), and Bein and Fütterer (1977). Shelf sediments vary greatly from coarse sands to muds, and are generally coarser near the shelf edge. Grain sizes decrease with depth on the continental slope (Figures 4(a), (b)). However, it is interesting to note a sharp decrease in sand contents between 500 and 800 m water depth in the north (Figure 1, profiles A–C; Figure 4(a)) and between 300 and 500 m south of C. Blanc (Figure 1, profile E; Figure 4(b)). Off the Senegal mouth silts and clays are predominant. South of the Sengal in water depths of less than 500 m, sand contents are as high as 60–80% with medians between 120 and 500 μm and maximal sorting in 100–300 m water depth (Diester-Haass and Müller, 1979). Downwards from these water depths

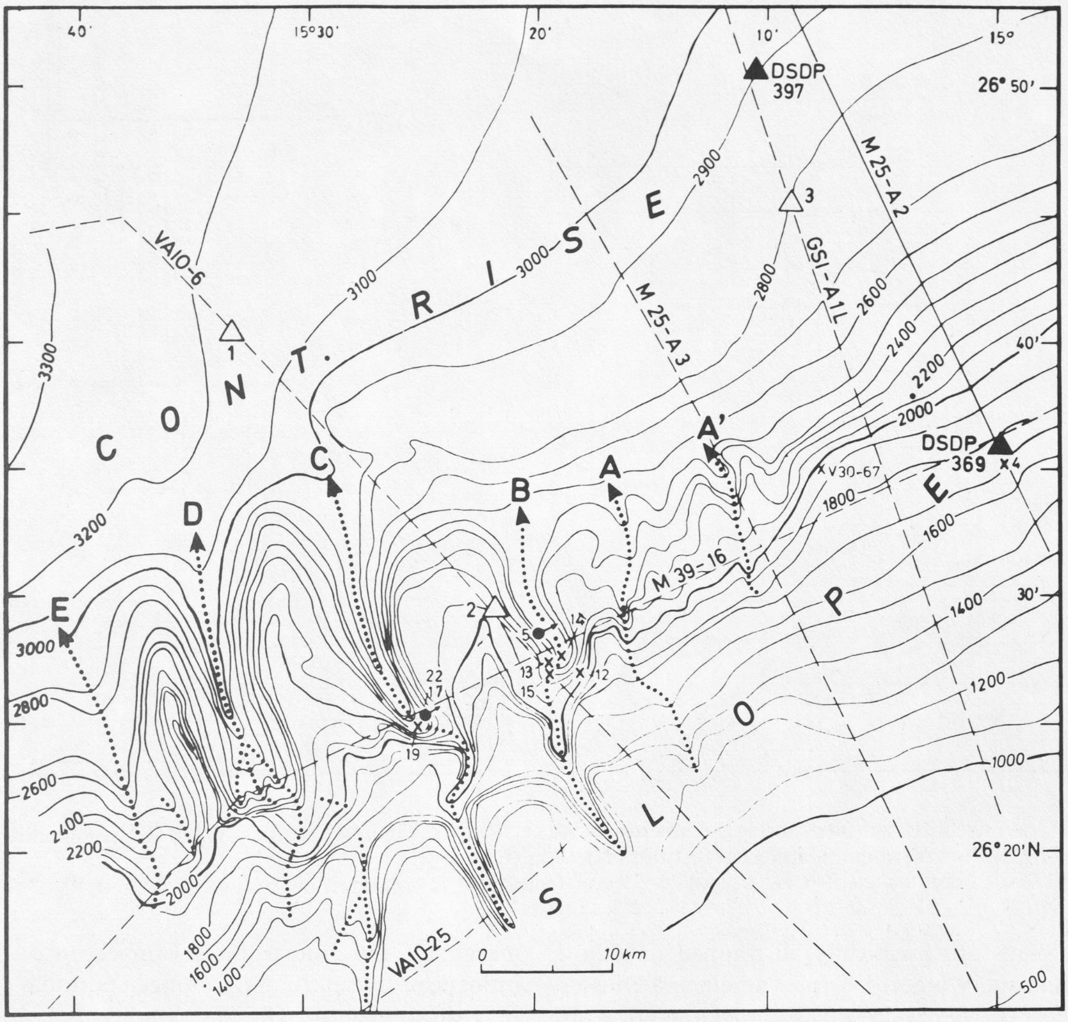

Figure 3 Lower continental slope morphology westsouthwest of C. Bojador with axes of canyons A′–E. (After von Rad *et al.* (1979))

silt contents get more important with a gradual decrease of coarser silt and an increase of finer silt and clay, a result of winnowing by an undercurrent discussed on page 155. An exception occurs between the area south of C. Blanc and Nouakchott, where coarse silt prevails from the shelf to the lower slope. This can be explained by reference to the *carbonate contents*.

Carbonate is essentially of organic origin. Again shelf sediments vary substantially. North of C. Blanc high contents are caused by coarse grained biogenous relicts. South of it they are mixed with terrigenous carbonate-poor eolian and fluviatile supply. Lower slope and rise sediments are characterized by carbonates from planktonic foraminifera in the sand fraction and coccoliths in the silt and in the clay fraction (Figure 5). South of C. Timiris the marked carbonate minimum on the slope is caused by the high content of nearly carbonate-free eolian silt (Table 1) especially within the coarse fractions, transported mainly during strong wind periods (Bein and Fütterer, 1977).

Terrigenous *clay* supply is illustrated in Figure 6. There is a general decrease of illite from north to south, no drastic changes in kaolinite and an increase of montmorillonite both from north to south and from shallow to deep water (except off the Senegal mouth). This distribution illustrates both the climatic zonation (Figure 1) and sorting effects.

Current investigations of *sediment sources* by the Kiel marine geological group demonstrate the overwhelming contribution of *eolian* and biogenous particles to the sediments offshore.

Recent dunes consist of well-rounded sand with median diameters around 200 μm and only up to 2% fractions less than 63 μm. Small amounts of mica and feldspars are present. The finer material is blown out by the wind and is transported as a loess-like dust offshore. Near Mauretania/Senegal mostly silt settles out as demonstrated in Table 1 and discussed

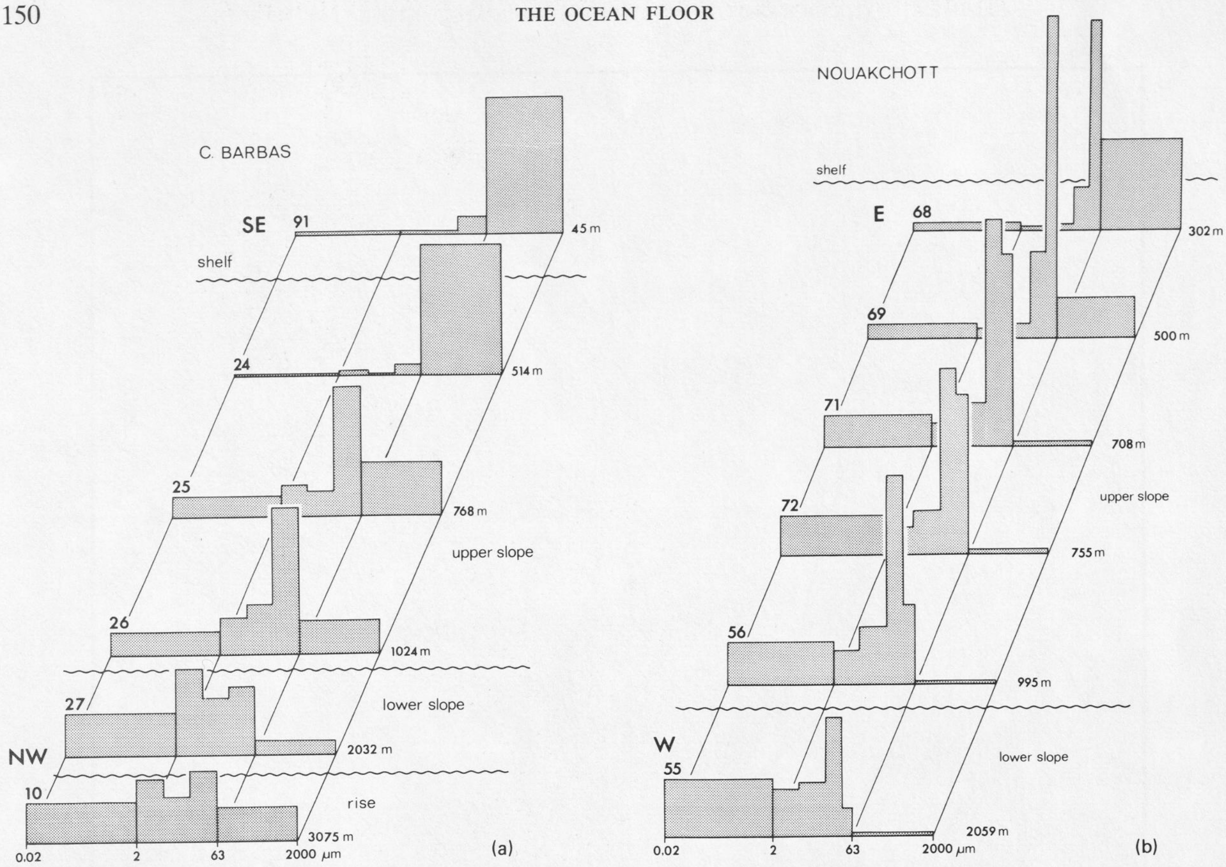

Figure 4 Grain size distribution of surface sediments off: (a) C. Barbas (Figure 1, profile C); and (b) Nouakchott (Figure 1, profile F). Station numbers: Geological Institute, Kiel University (profile C: 91 = 12,391 etc., profile F: 68 = 13,268 etc.). Silt fractions are 2–6, 6–20, and 20–63 μm. Coarse silt is separated in (b) into 20–40 and 40–63 μm

above. Sands are practically all trapped nearshore (Sarnthein and Walger, 1974; Sarnthein and Diester-Haass, 1977). Nearshore dusts are characterized by Johnson (1979): 'total' clay minerals 27%, quartz 30%, plagioclase 10%. dolomite 0.7%, but there are wide variations due to different source areas (Emery *et al.*, 1974; Sarnthein, 1978a, c) and sorting effects during transport.

On the shelf most of these dusts are winnowed out by waves and currents. In slope sediments they are concentrated off the southern margin of the Sahara, i.e. south of 20°N. Because this area at the northern margin of the Intertropical Convergence Zone is influenced by seasonal and longer periodic changes of arid and humid climatic conditions, with more important variations during Pleistocene, these dusts contain high percentages of red (Fe-hydroxide coated) quartzes. At present only some few percentages of stained quartzes are found in the Baie du Levrier behind C. Blanc for example (Koopmann *et al.*, 1979). Near the shore 'fall-out' dust distribution—after evaluating similarity coefficients given in Johnson (1979)—differs somewhat, probably due to station densities.

Table 1 Sediment characteristics in the Senegal mouth area. Data after Lange (1975), Kiper (1977), Lange and Fütterer (unpublished)

	Shelf sediment	Shelf mud	Senegal mud	Air-borne dust	
				inshore	offshore
clay, <2 μm (%)	6–12	32–40			6–18
silt, 2–63 μm (%)	10–20	57–68			79–93
sand, >63 μm (%)	70–80	0.5–3.4	1.3–22	86.9	<3.5
Md-sand (μm)	85–800	150	70–140	105	~70
carbonate (%)	50–60	20–30	<1	0.2	<4
red quartz, 63–125 μm (%)	35–55	35–55	35–60	73.5	
typical features	forams	plant remains			fresh water diatoms
		benthos	fecal-pellets		

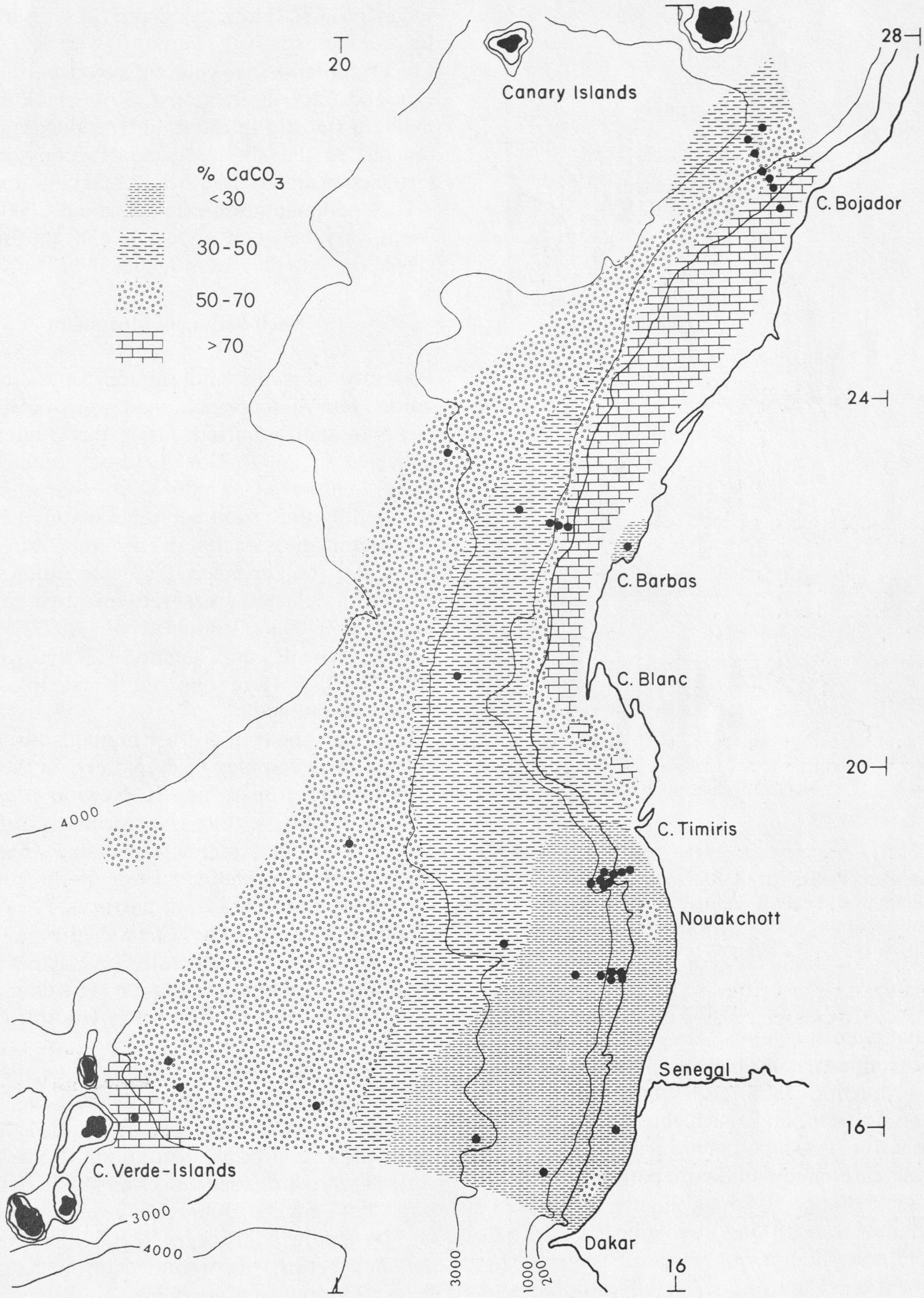

Figure 5 Carbonate content of surface sediments (weight % $CaCo_3$)

These dusts and other sediment parameters were used to decipher the Pleistocene and Neogene Sahara climatic history as discussed in Lutze *et al.* (1979), Sarnthein (1979), and Sarnthein and Koopmann (1980). It is interesting to note that several climatic units have very sharp boundaries in the sediment cores, sometimes to be seen directly by colour changes. Desert phases frequently lasted only for some centuries to millennia (Sarnthein, 1978a).

Input of terrigenous particles by *rivers* was only studied at the Senegal mouth. Senegal sediments contain up to 20% sand with median diameters

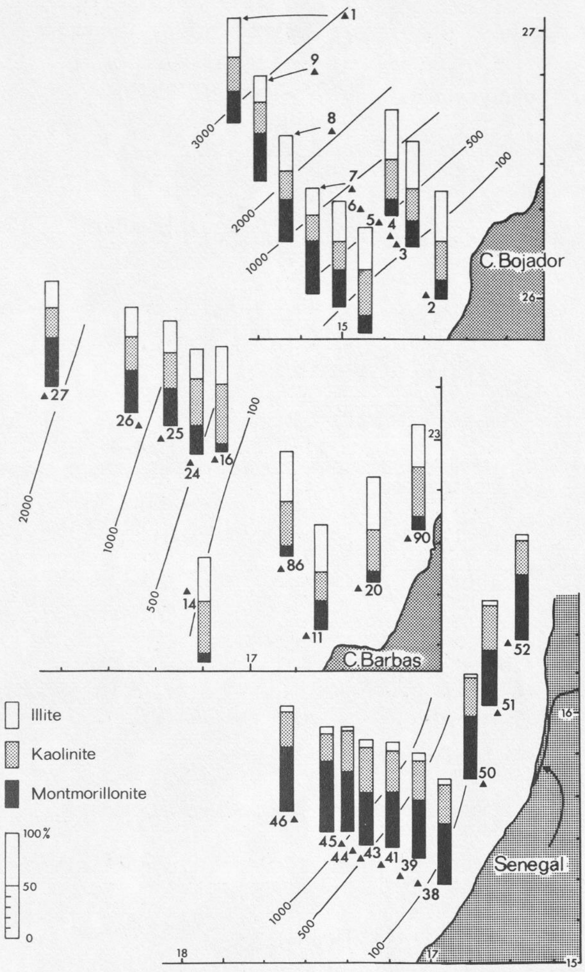

Figure 6 Percentages of X-ray intensities of the main constituents of the clay fractions ($<2\,\mu$m). Water depths in metres; station numbers: Geological Institute, Kiel University (1 = 12,301 etc.). After Lange (1975)

around 100μm. Characteristics are siltite aggregates, mica, and plant fragments. They are nearly carbonate-free, contain a considerable portion of red quartzes in all fractions between 63 and 500μm (Kiper, 1977 and Table 1) and reach the shelf only during autumnal river floods. Offshore they are mixed with biogenous carbonates. Fines are partly concentrated on the shelf (Lange, 1975 and Figure 10) and cover the continental slope and rise, especially in water depths of more than about 500 m off Senegal.

As mentioned above, nearly all carbonates are supplied by *organisms* (Fütterer, 1977). In the sand fractions of shelf stations molluscs prevail, on the slope planktonic foraminifera are predominant. Carbonate silt particles (Figures 7(a), (b)) from benthic organisms decrease from the shelf (20–>50%) to the lower slope (<10%) as a result of decreasing productivity. Planktonic particles increase from less than 10–20% on the shelf to about 30–40% on the lower slope north of C. Blanc. For example, total sediment in 3075 m water depth off C. Barbas (profile C, Figures 1, 7(a), station 10) with 56.2 weight % $CaCO_3$ contains 28% coccoliths (concentrated in the clay and fine silt fractions), 30% planktonic foraminifera (mostly in the sand fraction), 5% benthic remains in the silt and sand fractions, and 37% terrigenous material in the silt and clay fractions.

Bulk sedimentation rates in about 2000 m water depth vary between about 70 and 100 mm/ka. In glacial periods they were higher by a factor 2.

Shelf Sediment Movement

Presently, currents and surface waves intensively erode, retard deposition, and re-work shelf sediments or they occurred during the Quaternary, as indicated by small cliffs, hardrock outcrops, sand waves, elongated ‘windows’ of coarse sand surrounded by finer sand and relict material.

General shelf facies descriptions are given in McMaster and Lachance (1969) and Summerhayes *et al.* (1976). Selected areas were investigated by Newton *et al.* (1973), Einsele *et al.* (1977), Milliman (1977), Piessens and Chabot (1977) and Koopmann *et al.* (1979). Here only three examples will be shortly mentioned.

Side scan sonar and other methods distinguished an extremely complex facies pattern on the shelf off C. Barbas (Figure 1, area X, Newton *et al.*, 1973). The outstanding feature is a patchiness often within a less-than-one kilometre scale (Figure 9). Sedimentological characteristics of the sands indicate bottom currents from northeast to southwest, therefore following the Canary current, but also from southwest to northeast. Wave action from the northwest—the normal situation according to Emery *et al.* (1974)—moves sand partly landward in water depths of at least 60 m.

Spatial and temporal patchiness of the organic matter content is illustrated off the Senegal mouth (Figure 1, area Z, Figure 10, Domain, 1977, 1978).

Recent lateral facies distribution can be found in vertical vibro corer sequences as shown in Figure 11 (area Y, Figure 1). Details are given in Einsele *et al.* (1977). During Pleistocene regressions this part of the shelf became incorporated in the Sahara dune fields. During transgressions the sands were reworked and mostly swept over the shelf edge and into nearby canyon heads. Only about 1/10 remained on the shelf.

Downslope Movement

‘Grain by grain’ transport

A substantial fraction of the sediment particles crossing the shelf edge are transported downslope ‘grain

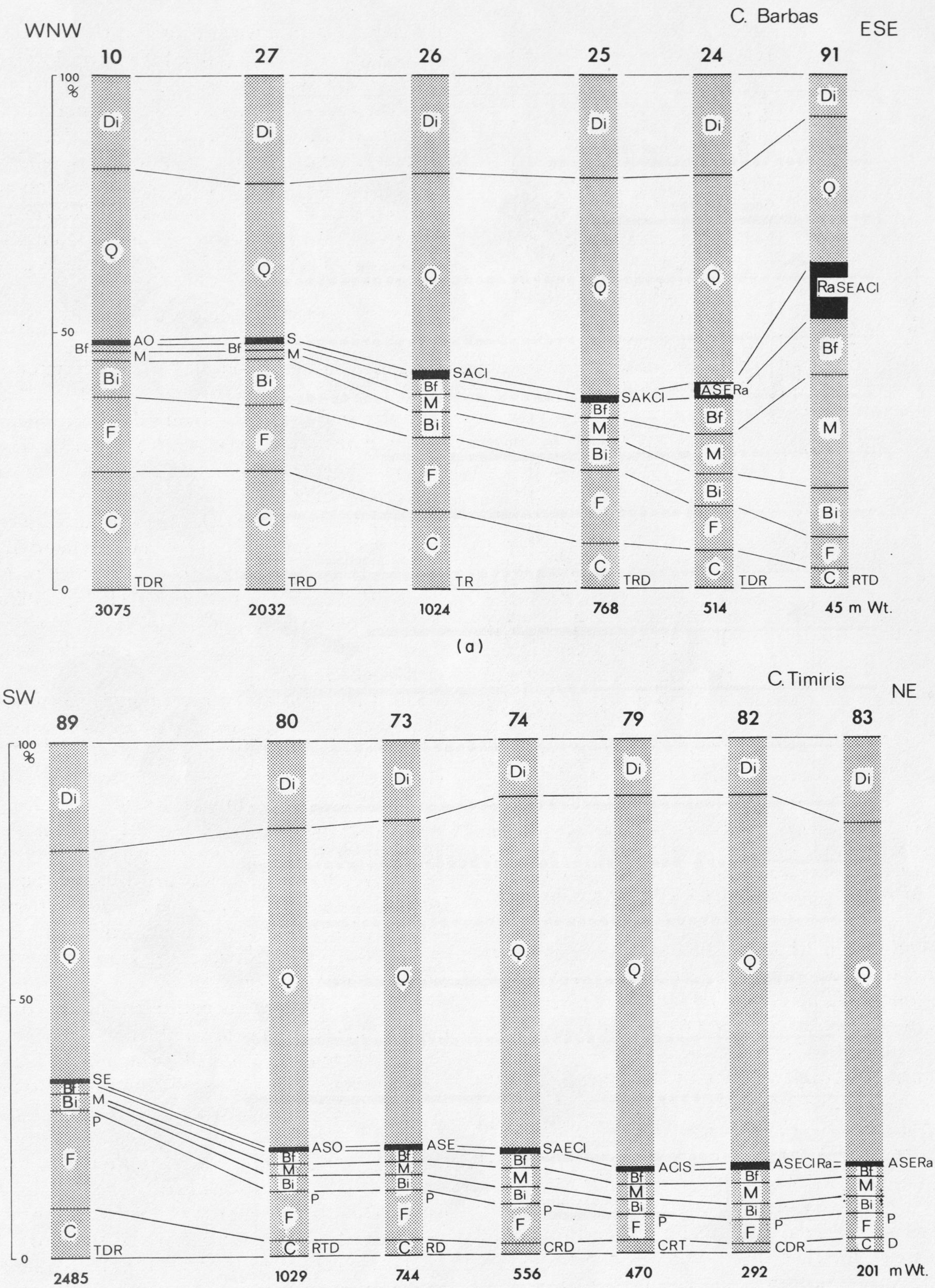

Figure 7 Composition of silts in surface samples off: (a) C. Barbas (Figure 1, profile C); and (b) C. Timiris (Figure 1, profile E). Di, undetermined terrigeneous particles; Q, quartz, Bf, benthic foraminifera; M, benthic molluscs; Bi, undetermined biogeneous particles; F, planktonic foraminifera; C, coccoliths (T, thoracosphaeres; R, radiolarians; D, diatoms); S, siliceous sponges; E, echinoderms; O, ostracods. Benthic constituents used as downslope transport indicators: K, octocorals; Ra, red algae; A, ascidians; Cl, boring chips of clionid sponges (in black)

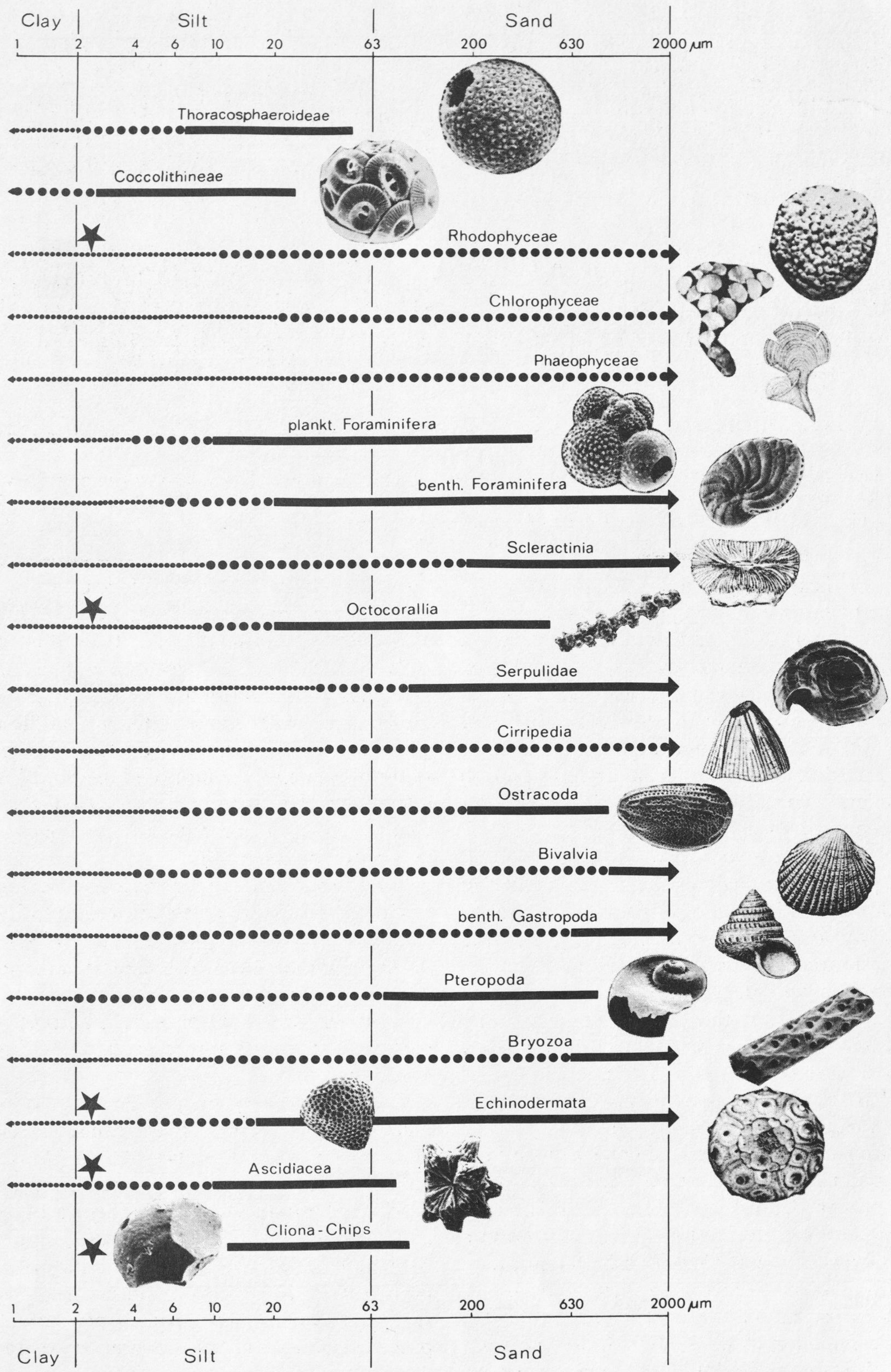

Figure 8 Grain sizes and identification limits of biogeneous carbonate skeletons or particles. Asterisks mark downslope transport indicators used off northwest Africa

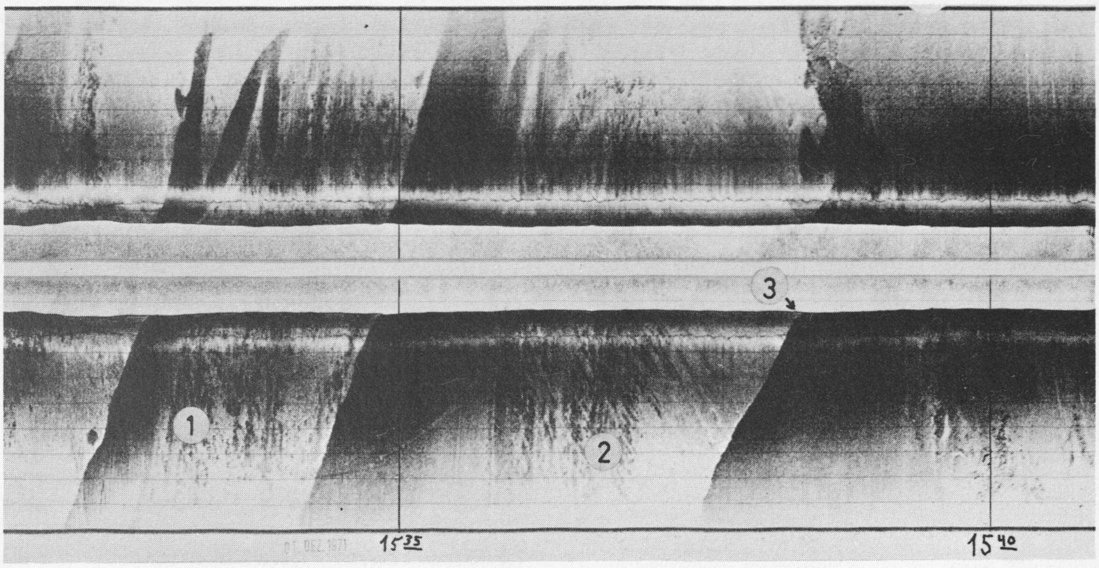

Figure 9 Shelf sediment patchiness off C. Barbas. Side scan sonograph from area X, Figure 1. Asymmetrical window cut through fine, upper sand layer (light) exposing coarse sand beneath (dark) fields of Pinna with lineations (1,2). At (3) sharp, roughly 1 m high, southeast-facing slope of window, approximately 56 m water depth. Sonograph is about 2 km long and each half about 170 m wide. (After Newton *et al.* (1973)

by grain'. Indications are given by the grain size distribution mentioned on page 150 and discussed in Bein and Fütterer (1977) and Bein and Sass (1978). Glauconite and other shelf relict materials, and thick shelled benthic shallow-water pelecypods in slope sediments are mentioned in Diester-Haass (1975) for example. Silt of shallow-water origin as red algae or ascidiae particles, and cliona boring chips (Figure 8) reach the lower slope and rise north of C. Blanc, but not as deep south of it (Figures 7(a), (b)). Lutze *et al.* (1979) give impressive figures for benthic foraminifera displaced from shallow waters to about 2800 m off C. Bojador (Figure 1, profile B, near DSDP site 397): up to 3% of the benthic forams in the 125–250 μm fraction and 15–25% in the 63–125 μm fraction were displaced. Therefore it is estimated that roughly one-third of the total sand fraction may have been transported down the relatively steep slope there (Lutze *et al.*, 1979).

What kind of *water movement* may be responsible for this transport? Up to now only scanty direct observations exist. Off Sierra Leone near-bottom currents originating from internal waves were measured in water depths from 250 to 1000 m with maximal velocities between 10 and 40 cm/s in bottom distances between 6 and 16 m (Fahrbach and Meincke, 1978). Up- and downslope water movements due to tidal oscillations were observed on the US Atlantic continental slope at 38°N in 850 m water depth by McGregor (1979). Occasionally contour-following current events with velocities of about 30 cm/s occurred some 3 m above bottom.

Poleward flowing under currents in water depths between about 100 and 600 m were observed on the northwest African slope from Senegal to C. Bojador with a general deepening to the North (Mittelstaedt, 1972, 1976, Mittelstaedt *et al.*, 1975; Johnson *et al.*, 1975). In 150 m water depth daily mean speeds of 7–20 cm/s were measured. Figure 12 gives an idea of the complex water movements in a profile between C. Blanc and C. Barbas. Even some downslope water movements are indicated therein. Winnowing effects by this current can explain the sudden changes in sand contents on the upper slope as mentioned on page 148.

On the outer shelf of Sierra Leone McGrail (1977) calculates near bottom velocities of up to 25–40 cm/s in water depths of 40–80 m. The activity of this 'Canary Counter Current' is indicated there by sediment parameters, too.

Even very weak currents can transport sediment particles if they are stirred up from the bottom by *organisms*.

Continuous television profiles and the extremely high bioturbation effects in all sediments of the slope and upper rise off northwest Africa (Wetzel, 1981) indicate the importance of this mechanism. Fish may touch the bottom occasionally (Figure 13(1)) or use and possibly produce large holes (Figure 13(2)). Numerous crabs were observed running over the sea floor surface. Burrowing organisms near the surface stir up sediments. All particles displaced by these processes ultimately tend to move downslope.

Sediment mass movements

Slides, slumps, and debris flows on the northwest African continental margins are discussed in Embley

(1975, 1976), Hinz *et al.* (1973), Jacobi (1976), Moore (1977), Rona (1970), Seibold and Hinz (1974), Seibold *et al.* (1976), Summerhayes *et al.* (1971), Uchupi *et al.* (1976), and Embley and Jacobi (1977).

Echo sounder and seismic profiles indicate a wide area influenced by mass movements off the Sahara. They normally occur below 2000 m water depths, evidently combined with the steeper slopes there (Figures 1, 2, profiles B, C). Off the Senegal mouth slump escarpments with more than 100 m height and 16–42° slope angles were observed in less than 500 m water depth and on a continental slope with original angles of 1–3°. The escarpment surfaces incised in Tertiary sediments are buried by hemipelagic mud, sometimes only a few decimetres thick, and characterized by burrows and oxidation crusts. Debris flow masses settle at the base of the continental slope but some of them may reach transport distances of more than 500 km on the continental rise with slope angles of less than 1°. Areas of some hundreds to 20,000 km^2 are reported to be covered by these masses, ranging from decametres to about 200 m thick. Their boundaries in the transport area are sometimes marked by 50–150 m high, steep scars (Seibold and Hinz, 1974, Figure 6). The internal structure of these masses is chaotic as illustrated by box cores and appearance on seismic profiles (Figure

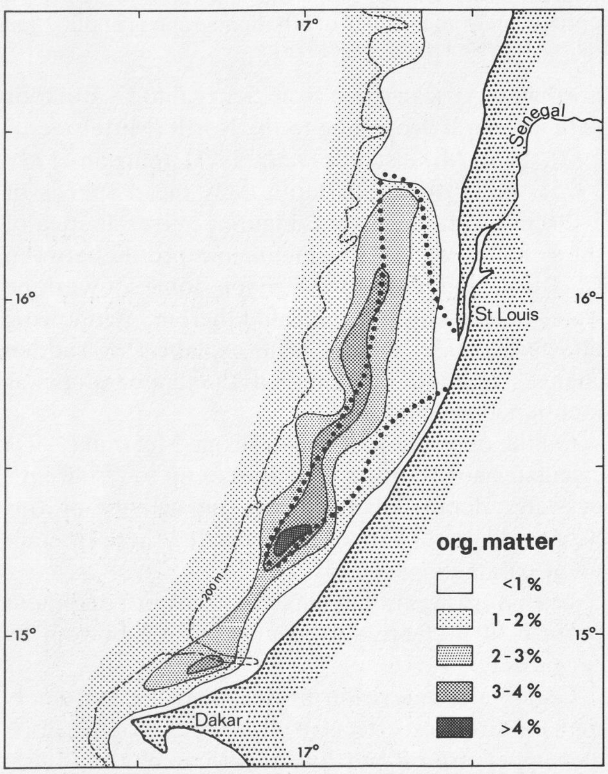

Figure 10 Shelf sediment patchiness off northern Senegal. The organic matter content ($= C_{org} \times 1.8$) is related to fine-grained sediments concentrated between 50 and 80 m water depth. Points indicate the area with more than 75% < 63 μm, clearly the result of Senegal river input, which is partly diverted to the north due to northernly currents (see Lange, 1975). Another maximum occurs at the Cayar Canyon head. The situation as given here for May 1970, e.g. the end of the cooler season, changed dramatically in September 1974, i.e. the end of the hot season, with a decrease of organic matter content up to 4:1. This may be caused by seasonal or long-term variations. (After Domain (1977, 1978))

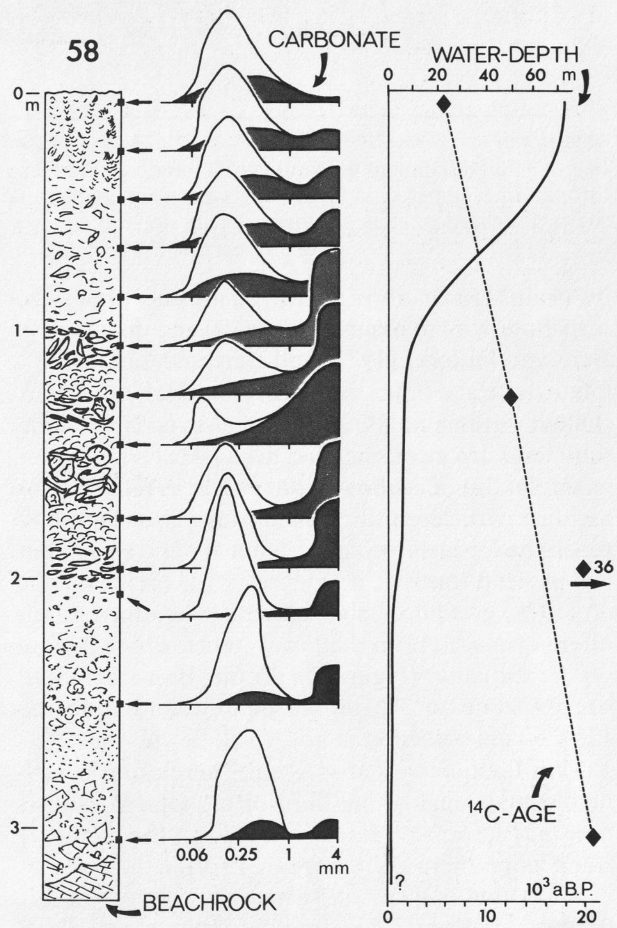

Figure 11 Vertical facies variations in shelf sediments. Vibro core, *Meteor* cruise 25, 1971, station 12358, 18° 18′N, 16° 23′W, 74 m water depth. Grain size distribution, carbonate content, and analysis of faunal associations are used for a bathymetric interpretation. Together with ^{14}C age determinations late Quaternary sea level changes can be studied. The latest transgression is indicated by lagoonal beach and open coast foreshore sediments between 3 and 2 m overlying beach rock cemented during an earlier regression. Between 2 and 1 m sediments from shallow water or former beach-lagoonal systems follow. From 1 m to the surface faunal associations reveal a sequence of sediments from water depths of 0–?20, ?20–50, 35–60, and 50–80 m respectively, based on analysis of recent faunas. (Simplified after Einsele *et al.* (1977))

14). In a hemipelagic matrix mud balls up to 30 cm in diameter occur. They may be rounded or elongated, therefore indicating plastic flow. Folds, faults, feather joints, cleavage planes, and a sort of layering due to shearing during slide movement occur (F. Werner, personal communication). Detailed analysis of the coarse grains, benthic foraminifera, and diatoms in the mud balls indicate several original sedimentation depths: Some 1000–1500 m off C. Bojador and near the shelf break off Mauretania and Senegal (L. Diester-Haass, F. Haake, and H. J. Schrader, personal communication). In all of our cores slumps and flow masses were covered by some decimetres of hemipelagic autochthonous muds. U. Pflaumann determined some ages of the lowermost undisturbed layers off Senegal/Mauretania. The last mass movement occurred at about 10–11 ka B.P. when sea level rise was very fast and reached more than 10 m/ka. As a consequence at least off the Senegal rivers, overloading of prograding sediments at the shelf edge triggering downslope mass movements suddenly ceased.

The causes of the mass movements off the Sahara originating in deep water, however, are unexplained. Undercutting of the continental slope by geostrophic currents as illustrated by the dramatic Oligocene event off C. Bojador (Arthur *et al.*, 1979) may be a likely explanation.

A further problem is whether the uppermost contacts between pre-Pleistocene allochthonous series and autochthonous hemipelagic or pelagic sediments is an age indicator for rapid sea level rise. As Pitman (1978) mentioned, rates of sea level

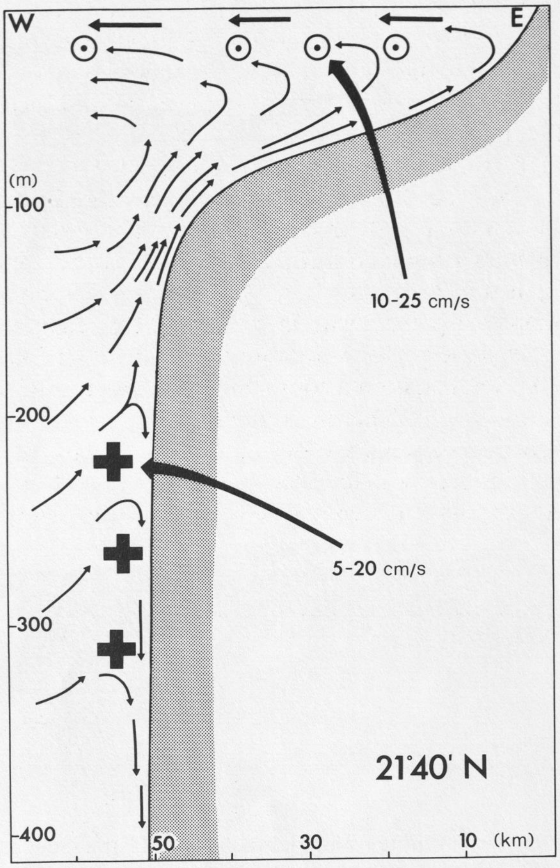

Figure 12 Undercurrents at the upper continental slope (21° 40′N). Equatorward flow indicated by circles, poleward flow by crosses with overall mean velocities during upwelling season. (Simplified after Mittelstaedt (1978))

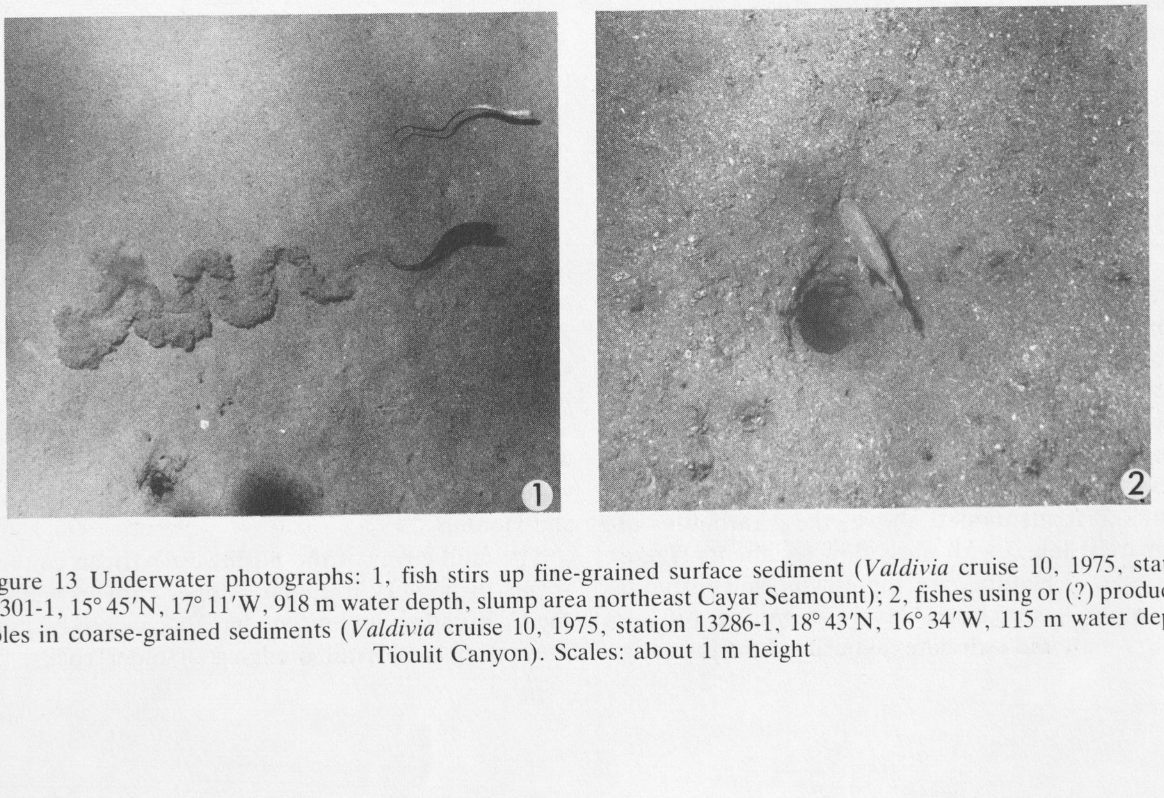

Figure 13 Underwater photographs: 1, fish stirs up fine-grained surface sediment (*Valdivia* cruise 10, 1975, station 13301-1, 15° 45′N, 17° 11′W, 918 m water depth, slump area northeast Cayar Seamount); 2, fishes using or (?) producing holes in coarse-grained sediments (*Valdivia* cruise 10, 1975, station 13286-1, 18° 43′N, 16° 34′W, 115 m water depth, Tioulit Canyon). Scales: about 1 m height

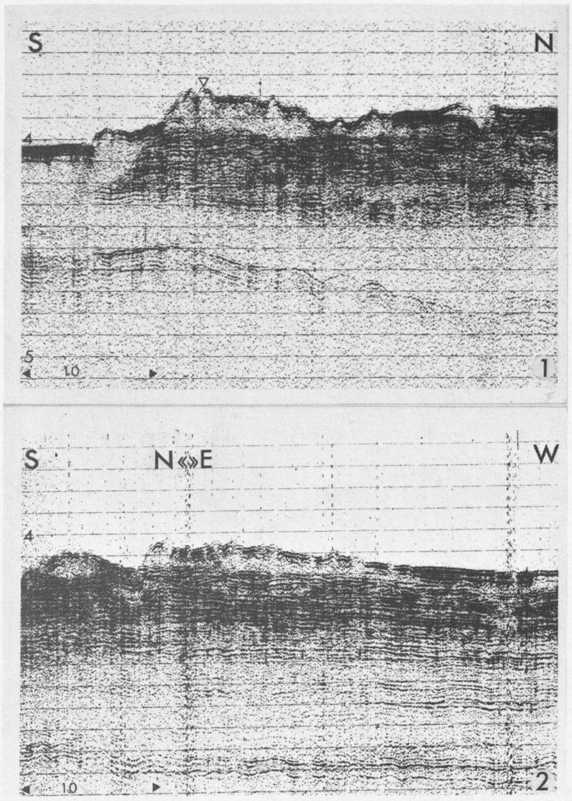

Figure 14 Turbidites and debris flows off the Senegal mouth. (1) Cross-section of turbidity current channels on the right with elevated natural levees and about 80 m deep on the left. In between debris flows. Triangle = box core 13205 (16° 11′N, 19° 55′W), about 125 km from shelf edge (2) Cross-section on the left of ship's course change position (16° 25′N, 18° 18.5′W), longitudinal section on the right. About 160 km from shelf edge. Seismic profiles from *Valdivia* cruise 10, 1975, courtesy of G. Wissmann, Bundesanstalt für Geowissenschaften und Rohstoffe Hannover. 4 s equal to about 3000 m water depth, 10 km distances.

Figure 15 Rocky canyon wall with sharp edged rock fall material. *Valdivia* cruise 10, 1975, station 13316-1, 13° 31′N, 17° 45′W, 1680 m water depth, Casamance Canyon. Scale: height about 1.5 m

changes may be more important for sedimentation than absolute figures of eustatic variations.

Turbidity currents

After the results of the Deep-Sea Drilling Project, turbidity current activity is well documented by turbidites off northwest Africa since the Cretaceous. Seismic profiles and gravity cores indicate widespread Pleistocene turbidites on the continental rise (Horn *et al.*, 1972; Embley, 1975; Jacobi, 1976; Young and Hollister, 1974; *Meteor* and *Valdivia* results). As mentioned above, these turbidites are intimately linked with mass flow sediments (Figure 14). Special features are the eolian sand turbidites indicating lowered sea levels, vigorous offshore trade winds, and a climate favouring dune formation as in glacial periods, but also during the Tertiary (around 20 million, 13 million, and 3–2 million years ago) (Sarnthein and Diester-Haass, 1977; Sarnthein, 1978b).

Up to now no coarse grained turbidite has been detected directly on the surface. Off Senegal a turbidite from the Dakar Canyon is covered by hemipelagic autochthonous mud with a base age of about 11 ka (F. Haake and U. Pflaumann, personal communication). Cores from the bottom of the Cayar Canyon (15°10″N) and the Tioulit Canyon (18°50″N) always had a centimetre to decimetre heavily bioturbated mud covering sands with Tertiary pebbles and coral rubbles (Seibold and Hinz, 1976). Therefore a very recent flushing by turbidity currents can be excluded. On the other hand continuous television observations in the Tioulit Canyon indicated that the lowermost 5–10 m of the canyon walls are less covered with mud and broken cables were reported in the Cayar Canyon area (Elmendorf and Heezen, 1957).

The mud cover of the northwest African canyons seems to be very irregular. Upper canyon walls in the C. Bojador canyons are largely covered by mud, preventing successful dredging of older rocks, but

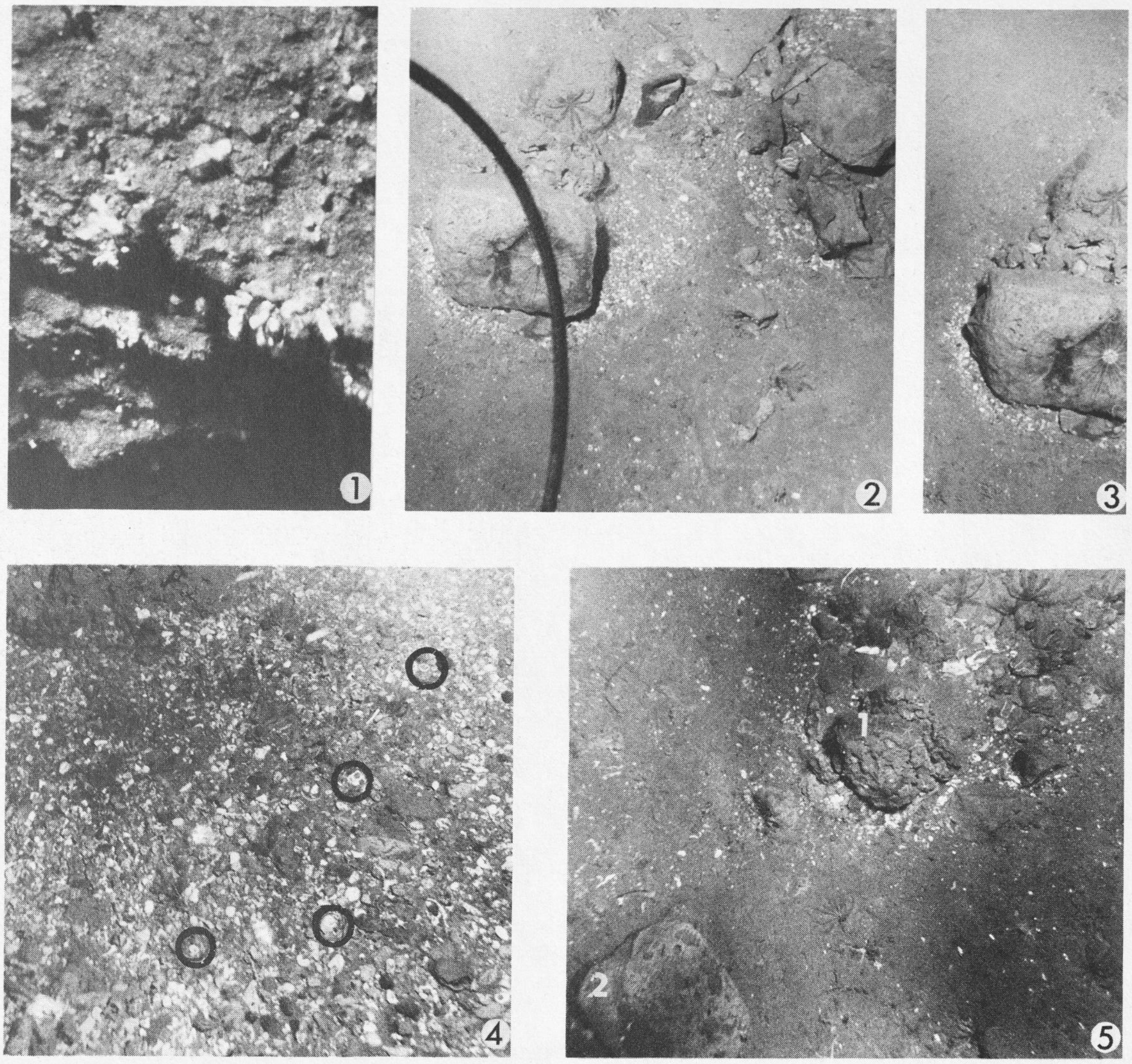

Figure 16 (1) Corals living in 170 m water depth. Cayar Canyon wall, 14° 59′N, 17° 18′W, *Valdivia* cruise 10, 1975, station 13303-1. (2,3) Rockfall blocks surrounded by mussel shell scour marks. Casamance Canyon, station 13316-1, 13° 31′N, 17° 45′W, 1760 m. (4) Same station: mussel shells, some of them hollow side up and filled with mud. (5) Same station: rockfall material with possible organic borings on blocks 1 and 2. Scale: heights about 1 m

frequently 5 m piston cores penetrated the mud (von Rad *et al.*, 1979). Between 350 and 550 m the Tioulit Canyon walls are covered by a very fine grained greenish mud with clear cut surface burrows but sliding downslope when touched by the television camera. On shallower slopes, living corals indicate the absence of mud sedimentation (Figure 16(1)). In the canyons off the Casamance area (13°30′N, 17° 45′W) walls are partly free of mud (Figure 15). Steep escarpments up to decametres in height, sometimes with overhanging walls and dissected by joints are separated by terraces with or without mud. They are mostly covered by rock fall material (Figures 16(2), (3)) up to cubic metres in size with different grades of rounding. Certainly mass wasting from submarine cliffs (Ryan *et al.*, 1978) is an important and continuing submarine morphological and sedimentological process.

In contrast to the observations of Ryan *et al.* (1978) only a few features that could possibly be related to rock boring organisms were detected (Figure 16(5)), but macrobenthos like anemones, sponges, and ophiuroids were always present. Rock fall material showed no preferred orientation and was sometimes mixed with mud, certainly an interesting but local sediment type in fossil series.

This irregular mud distribution proves current action throughout the canyons. This can be illustrated by light rings, sometimes asymmetric in shape around blocks and pebbles (Figures 16(2), (3)). The light parts consist of mollusc debris. Sometimes mussel shells show the hollow side up, filled with

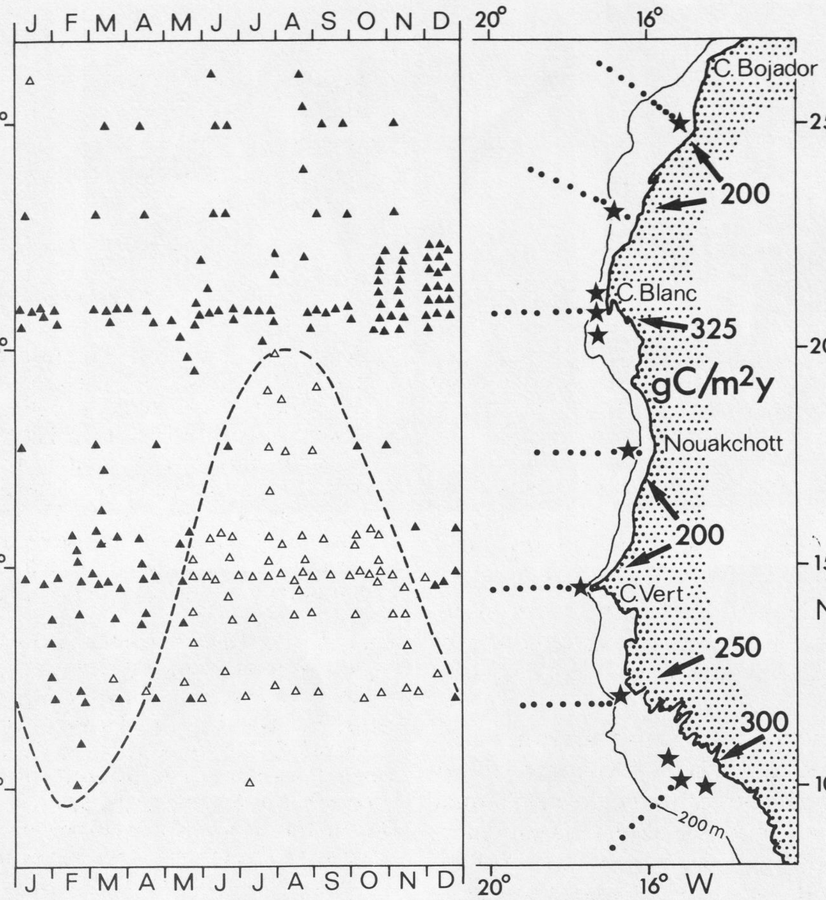

Figure 17 Variation of upwelling in space and time (left) and maximal values for annual primary production in upwelling areas (right). (Simplified after Schulz *et al.* (1978))

mud (Figure 16(4)). These scour marks point to tidal currents or internal waves as measured inside canyons, for example by Shepard (1975, 1976).

Sediments and Upwelling

Upwelling supplies water from subsurface layers to the surface layer causing cooler temperatures, lower salinities, and oxygen contents and higher nutrient concentrations in the photic zone. Therefore increased primary production by phytoplankton results, together with an abundance of zooplankton up the food chain to fishes.

Off northwest Africa coastal upwelling originates from trade winds, driving surface waters from the coast. This phenomenon occurs the year round between 20°N and 25°N (Figure 17), in summer up to Morocco and Portugal (Wooster *et al.*, 1976), in winter down to Sierra Leone (Schemainda *et al.*, 1975; Schulz *et al.*, 1978). However, only a small fraction of the organic input from surface waters reach the sediment and is incorporated finally because the organic material has to pass several filters destroying it mechanically, biologically, and chemically (Seibold, 1979). Even the so-called 'organic matter' content of sediments is a very questionable indicator for upwelling. 'Organic matter' may be of terrestrial or planktonic (or benthic) origin, may be contributed by clay mineral coatings, accumulate preferentially with fine particles, and is more protected by high bulk sedimentation rates. Off northwest Africa, slope an rise sediments contain 0.3–4% organic carbon. Holocene bulk sedimentation rates there vary between 20 and 130 mm/ka and accumulation rates of organic carbon between 0.05–1.5 g m^{-2} a^{-1} (Müller and Suess, 1979). After the primary production figures given in Figure 17 less than 0.7% of the surface production is incorporated in the sediments. Furthermore higher primary production may be caused by river input of nutrients as illustrated in the southern part of Figure 17. Off Sierra Leone coastal upwelling occurs in February/March only. Nevertheless high primary production rates were measured there. Even in water depths of more than 1000 m organic carbon contents of surface

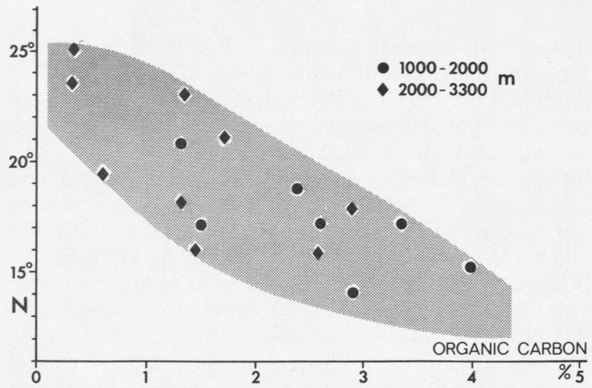

Figure 18 Organic carbon contents of surface sediments from the continental margin of northwest Africa. (Simplified after Diester-Haass and Müller (1979))

sediments increase from areas with upwelling during 12 months in the North of Senegal, where upwelling is restricted to about six months (Figure 18). Diester-Haass and Müller (1979) discuss several factors possibly responsible for these facts. As a result organic matter content may be only an indicator for upwelling in special environments as off southwest Africa.

The same holds true for most of the other sediment particles used up to now to characterize upwelling, for example the ratios benthic/planktonic foraminifera or radiolarian/planktonic foraminifera (Diester-Haass, 1977; Diester-Haass and Müller, 1979). They are influenced by differential fractionation, dissolution, and sorting effects. Therefore planktonic foraminifera indicating relatively cool surface waters seem to be the most reliable indicators as demonstrated off northwest Africa by Pflaumann (1975) and Thiede (1975) and discussed in Seibold (1979).

Combining several sedimentological criteria coastal upwelling seems to have been more active during glacial periods either as a result of stronger northeast Trade winds or otherwise intensified water mixing near the lowered shelf edge (Diester-Haass *et al.*, 1973; Sarnthein and Walger, 1974; Müller, 1975; Seibold *et al.*, 1976).

Conclusion

In general the modern slope and rise seem to be stable. They receive less than 100 mm of sediment in 1000 years. During glacial periods sedimentation rate increased by a factor of 2, mostly as a result of higher eolian input. Stronger winds and a concentration of water movements near the present shelf break, increased coastal upwelling during lowered sea level phases. Spectacular events revealed by recent research were extended gravity mass movements and turbidity currents from the open slope, within pre-existing submarine canyons or originating from active longitudinal sand dunes reaching the shelf edge. These events shaped the continental margin and its sediment cover much more than the contemporary processes.

Sometimes, therefore, the past only may be the key to the past.

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